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Deploying AL-FEC protection with online algorithms for multicast services over cellular networks

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Abstract Reliability control is a key concern on the evolution of mobile multicast services. To this direction, the use of forward error correction (FEC) on the application layer is widely adopted in several mobile multicast standards. FEC is a feedback free error control method, where the transmitter introduces in advance redundant information within the source data to enable receivers recovering arbitrary data erasures. On multicast delivery where retransmission-based error recovery methods are not efficient, the most suitable error control method is the use of application layer forward error correction (AL-FEC) codes. In this work, we introduce novel AL-FEC deployment policies over mobile multicast environments utilizing online algorithms. We aim at the efficient application of AL-FEC protection with RaptorQ codes over multicast delivery in the context of competitive analysis. We provide a competitiveness analysis model of AL-FEC application over mobile multicast environments. Furthermore, we propose two online algorithms adjusting the introduced redundancy of AL-FEC protection according to several FEC encoding parameters and constraints of mobile multicast delivery.

Keywords Forward error correction · RaptorQ · Mobile multicast networks · Online algorithms · Competitive analysis

1 Introduction

Forward error correction (FEC) is a protection method against packet losses adopted in several mobile multicast standards. FEC concept, unlike the common methods of error control (e.g. ARQ, Carousel), is based in its "forward" feature. In FEC application redundant information is transmitted in advance with the source data in order to enable a receiver to overcome data erasures, making FEC a feedback-free mechanism. The feedback-free feature of FEC perfectly matches the individual constraints of a radio multicast transmission where feedback reports are costly or even impossible [1]. Based on this, several mobile multicast standards have introduced FEC protection on the application layer (AL-FEC) of its multicast services boosted by powerful AL-FEC codes, i.e. Raptor codes family [2], that have recently emerged.

However, FEC protection comes with its own cost since controlling the introduced redundancy is not a trivial issue. The multicast sender should introduce enough redundancy on the transmission so as to ensure that the recipients will be able to reconstruct the transmitted object recovering arbitrary data losses. At the same time, the amount of redundant information should be adapted at the current reception conditions to avoid resources wastage. It is obvious, especially on mobile environments, that the design of a feedback-report mechanism aiming to control

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the FEC encoding parameters is complicated due to the individual constraints of multicast environments or even impossible due to the variability of the radio propagation medium. Furthermore, on real-time content delivery, where data reception is tightly time-constrained, the use of retransmission-based methods to confront packet losses is not appropriate. An efficient method to obtain reliability to the real-time service transmission is to introduce enough redundancy (i.e., the AL-FEC transmission overhead) so that each packet is transmitted only once. Consequently, the multicast sender should decide on the most suitable amount of overhead it will transmit, in order to cope with different receiver's packet loss rates. Moreover, the transmitter has to decide on the amount of protection that should be introduced to each encoded AL-FEC source block upon its construction without prior knowledge on the packet loss conditions has to confront. Based on this, the design of an algorithm adjusting the introduced AL-FEC transmission overhead can be reduced to the basis of an online problem. Online problems assume that complete knowledge of the entire input is not available to an algorithm and the input is revealed in parts, with an online algorithm responding to each new input upon arrival.

In general, online algorithms [3] are used to confront problems where the input of the algorithm is not available in advance. Subsequently, online algorithms have to generate output without knowledge of the entire input since input, information arrives in the future and is not accessible at present. In some problems, where the application of deterministic solutions lacks of applicability, a randomized online algorithm [4] is the simplest available algorithm and some times the most efficient solution. The effectiveness of online algorithms is evaluated using competitive analysis. The main concept of competitiveness is to compare the output generated by an online algorithm to the output produced by an optimal offline algorithm. The competitive ratio of an online algorithm A is defined with respect to an adversary. In general, the adversary generates a sequence σ and the online algorithm A has to serve σ. When constructing the sequence σ, the adversary always knows the description of the online algorithm A. The optimal offline algorithm knows the entire request sequence in advance and can serve it with minimum cost. Formally, given a sequence σ, $A(\sigma)$ denotes the cost of the online algorithm A and $OPT(\sigma)$ denotes the cost of the optimal offline algorithm. An online algorithm A is called c-competitive if there exists a constant α such that $A(\sigma) - c \cdot OPT(\sigma) \leq \alpha$ [5].

In this work we utilize online algorithms to achieve efficient application of AL-FEC protection over mobile multicast environments. We propose two online schemes on AL-FEC deployment. A randomized online algorithm aiming at the efficient download delivery over mobile multicast services and a deterministic online algorithm targeting on streaming delivery for multicast real-time services. Both the proposed online AL-FEC protection schemes are able to provide reliable delivery requiring no knowledge on the network conditions. The randomized online algorithm aims to provide an AL-FEC deployment policy facing the main matter of argument in AL-FEC application, i.e. the efficient selection of the introduced transmission overhead. It is obvious that an arbitrary large amount of fixed overhead may lead to network resources wastage while, a small amount of overhead may have no effect on the transmission robustness. To this direction, we demonstrate that the proposed online strategy can operate surprisingly well under different loss patterns and network conditions without the need of costly feedback-report mechanisms. The deterministic online algorithm targeting on real-time services exploits the properties of RaptorQ AL-FEC codes and adapts the amount of AL-FEC introduced redundancy according to the AL-FEC source block length. More precisely, the deterministic algorithm reduces the number of transmitted AL-FEC repair symbols as the source block length increases. Thus, the proposed online scheme introduces adaptation nature on the RaptorQ AL-FEC application achieving a trade-off between robustness and user experience.

The pursuit of the presented work is to provide a competitive AL-FEC application framework under which several online algorithms on the AL-FEC application can be designed. Furthermore, we propose two feedback-free online algorithms which are able to provide efficient application of AL-FEC protection over mobile multicast networks.

The remainder of this manuscript is organized as follows: In Sect. 2 we provide an overview of the most important related works. In Sect. 3 we describe the competitive framework under which we design the proposed online algorithms and we introduce the analysis of the optimal offline algorithm. Section 4 presents the two online algorithms followed by the competitive analysis of each online scheme and in Sect. 5 we provide a performance evaluation of the online algorithms against the optimal offline instance. Finally, in Sect. 6 we provide our conclusions on the performance of the proposed online schemes and in Sect. 7 we highlight some possible steps that can follow this work.

2 Related work

Online algorithms are widely utilized in many research fields of mobile networks over several perspectives. The work presented in [6] proposes a data selection policy where, in the concept of competitive analysis, the decision of transmitting source data, retransmitting a packet or transmitting a redundant codeword is investigated. The authors provide a theoretical network model under which they design an online algorithm on choosing what data the multicast source should place in each sent packet. Furthermore, they provide trace-driven simulations to verify the effectiveness of the proposed scheme. The work presented in [7], examines the frequency assignment problem introducing distributed online algorithms. The examined online problem is abstracted as a multicoloring problem on a weighted graph and the authors propose a series of online algorithms on this basis. In the context of energy constraints and the design of routing algorithms, the authors of [8] propose an online algorithm on maximizing the throughput of multihop radio networks. In [9] online algorithms are utilized on multicast routing problems over energy-constrained ad-hoc networks. The authors propose two online algorithms on maximizing the capacity and lifetime of ad-hoc wireless networks and provide simulation results investigating the performance of the online algorithms. The work presented in [10] introduces a competitive online algorithm in terms of energy efficiency and delay in scheduling problems over wireless multicast environments. By reducing the energy-efficient transmission scheduling problem to a convex optimization problem, the authors design a variety of online algorithms aiming to minimize the energy required to transmit packets in a wireless environment. Furthermore, the authors of [11] present a set of randomized online algorithms studying the maximum independent set problem in disk graphs which can model resource allocation problems in mobile networks.

Moreover, a certain number of works have emerged aiming to provide adaptation nature on AL-FEC protection deployment over several perspectives. The authors of the work presented in [12] propose an adaptation framework for multicast video transmission over 3GPP video streaming services. They introduce the adaptation of the introduced AL-FEC protection based on the selected modulation and coding scheme (MCS) in conjunction with the scalable video coding (SVC) technique. In general, the authors of this work aim to provide a joint optimization framework of video coding, AL-FEC, and physical layer rate selection to enhance the end user experience. In [13], a feedback-report based algorithm is proposed for voice over IP applications. In this work, the redundant data introduced to the transmission are adapted based on RTCP packet loss reports. In more detail, the proposed algorithm considers the history of packet losses in the network before changing the amount of AL-FEC overhead to achieve better control on the amount of introduced redundancy. The authors of [14] present several adaptive algorithms on the introduced FEC protection over video streaming for Wi-Fi MANET networks. The authors utilize a packet loss rate feedback mechanism to adapt the rate of FEC-encoded redundant packets, the transmission rate and the modulation scheme to achieve reliable delivery of live video over multiple hops.

To the best of our knowledge, there is no previous work attempting to reduce the AL-FEC protection application to an online problem. Apart from this fact, considering the previously listed related works on adapting the introduced FEC redundancy over wireless delivery, it should be noted that the proposed AL-FEC adaptation framework can not be directly compared with the previous conventional algorithms. First of all the presented algorithms are online algorithms, which are evaluated utilizing competitive analysis under the competitive framework they are designed. Further to that, the proposed algorithms are totally feedback-free approaches. Hence the can not be compared with the previous listed algorithms which, are feedback-based approaches, a fact that is also opposed to the feedback-free nature of the AL-FEC protection.

3 Competitive framework

In this section we state the online problem and we present the utilized network model under which we design the proposed online algorithms. Furthermore, we describe the optimal offline algorithm and we present the competitive analysis of its transmission cost.

3.1 Problem formulation

Defining the online AL-FEC policy problem, the multicast source takes as input a sequence of packets and a set of encoding parameters and has to produce as output AL-FEC encoded symbols. The multicast source has to decide on the amount of AL-FEC overhead that will be introduced to the transmission, having no knowledge on the packet loss patterns of the network. The network model we utilize refers to a typical mobile multicast transmission environment. A multicast source transmits the same data to a fraction of users participating in the multicast delivery through a shared unreliable radio channel. The transmitted data, considered to be a continuous object, are encapsulated in a UDP/IP multicast flow, with the multicast source injecting packets into the network.

On the AL-FEC protection mechanism, we consider the application of the newly introduced RaptorQ FEC scheme [15]. The multicast sender introduces redundant information within the source data in order to enable multicast receivers to overcome independent packet losses and successfully reconstruct the transmitted data. On the AL-FEC encoding, the transmitted object is partitioned in one or several source blocks. Each FEC source block consists of k source symbols, with k depending on the selection of the encoding parameters. The size of a FEC source block is denoted as source block length (sbl). Through the RaptorQ encoding, for each FEC source block, a certain amount of redundant symbols, also called repair symbols, are generated according to the desired amount of protection introduced by the multicast source. A unique ID is assigned to each resulting encoding symbol, which can be a source or a repair symbol, in order to identify the type of the symbol according to the assigned value. At the receiver side, after the reception of the transmitted data each multicast user performs the AL-FEC decoding to recover the FEC protected source blocks. A multicast client is able to determine, for each FEC source block, which source symbols should have been received but have not and is also able to determine the number of encoding symbols it has received.

RaptorQ FEC is the newest member of Raptor codes family providing powerful capabilities on the AL-FEC protection application [16]. The performance of the RaptorQ AL-FEC code can be described by the decoding failure probability of the code, denoting the probability to fail on reconstructing the protected data as a function of the source block size and the number of received symbols. The decoding failure probability of RaptorQ code can be modeled by (1) [17]:

$$p_{f_{RQ}}(n,k) = \begin{cases} 1, & if \quad n < k \\ 0.01 \times 0.01^{n-k}, & if \quad n \geq k \end{cases} \tag{1}$$

In (1), $p_{f_{RQ}}(n,k)$ denotes the probability of a failed decode of a RaptorQ protected block with k source symbols if n encoding symbols have been received.

In this work, we assume the transmission of a packet sequence with independent packet loss masks applied to each multicast receiver according to an examined packet loss rate. On the utilized sequence of packets, each packet is denoted by the triplet $\{uid, sbn, (r_i, l)\}$ where:

- uid: is an ID identifying each AL-FEC resulting packet in each source block
- sbn: is the number of the FEC source block the specified packet is organized to
- (r_i, l): denotes if the specified packet is lost in the receiver i with the boolean l set to 0 if packet is lost

The packet loss pattern applied to the sequence of transmitted packets is denoted as p, corresponding to the average network packet loss rate. Variable p takes values in the range $[0, 1]$. At each multicast receiver, a packet loss mask is applied independently based on the value of p. Furthermore, the packet erasures are randomly distributed at the multicast receivers. Table 1 illustrates an instance of the loss transcript applied in a fraction of multicast users. In more detail, Table 1 presents the successful or not reception of 10 transmitted packets at 5 multicast receivers with the value of p fixed at 0.2 inline with the assumptions of the presented network model. Each line of the table refers to a user participating in the multicast delivery and each column to a transmitted packet. The values of the table refer to the outcome of each packet reception according to the doublet (r_i, l) as described above. Moreover, we assume that the packet loss mask is randomly distributed at the whole fraction of the transmitted object and each transmitted packet contains one AL-FEC symbol of fixed length.

At each multicast receiver the AL-FEC decoding process is modeled according to the decoding failure probability of (1) in order to denote the examined AL-FEC source block as successfully reconstructed or not. For the decoding process, we assume that a sufficient threshold for the failure probability of a recovered source block is 10^{-2} or less as proposed in [18].

3.2 Offline optimal algorithm

Regarding the cost of the optimal offline algorithm, we assume that a multicast transmitter, with a priori knowledge of the packet losses pattern of the system, will introduce a certain number of redundant symbols. The examined AL-FEC policy problem is a cost minimization problem. Based on this, the optimal policy from the transmission cost perspective is not the introduction of a huge amount of overhead aiming to enable the higher packet loss user to successfully recover the transmitted object. Subsequently, the optimal algorithm should introduce the minimum number of required redundant symbols so as to cope with the average value of packet loss, aiming to satisfy as many users as possible. The scheme that can ensure the optimal selection of the transmission overhead is described by a multicast source that selects the introduced redundancy to a value close to the average packet loss rate of the network as denoted in [19]. In the present analysis, the multicast sender can exploit the practically zero reception overhead of RaptorQ code. As described in (1), RaptorQ can achieve the specified failure probability threshold requiring to receive no more additional symbols than the number of the transmitted symbols. Subsequently, the optimal AL-FEC selection policy can introduce as many repair symbols as the average number of lost symbols in the multicast users. Based on this, the number of repair symbols r the optimal offline algorithm will introduce in each source block can be computed as: $r \geq (sbl + r) \cdot p$.

Consequently, the cost of the optimal offline algorithm for each source block, defined as: $OPT = sbl + r$ can be described by (2):

$$OPT = \frac{sbl}{1 - p} \tag{2}$$

4 AL-FEC online schemes

In this section we introduce the proposed online algorithms for the AL-FEC policy online problem and we provide the

Table 1 An instance of packet erasures

User 1	(1,0)	(1,1)	(1,1)	(1,1)	(1,1)	(1,1)	(1,1)	(1,1)	(1,0)	(1,0)
User 2	(2,1)	(2,1)	(2,1)	(2,1)	(2,1)	(2,1)	(2,1)	(2,1)	(2,1)	(2,1)
User 3	(3,1)	(3,0)	(3,1)	(3,1)	(3,0)	(3,0)	(3,0)	(3,1)	(3,1)	(3,0)
User 4	(4,1)	(4,1)	(4,1)	(4,1)	(4,1)	(4,1)	(4,0)	(4,1)	(4,1)	(4,1)
User 5	(5,1)	(5,1)	(5,1)	(5,0)	(5,1)	(5,1)	(5,1)	(5,1)	(5,1)	(5,1)

competitive analysis of each online scheme. At first we introduce a naive randomized online algorithm for download delivery and thereafter we provide a deterministic adaptive online scheme targeting in streaming delivery over mobile multicast networks.

4.1 Randomized AL-FEC online algorithm

In this part we present a randomized online algorithm on the selection policy of the introduced AL-FEC redundancy on a multicast transmission. The proposed Algorithm 1 processes a sequence σ of packets according to the selected *sbl*, selecting equiprobably a value i when a source block is formed. The value i denotes the introduced transmission overhead, and takes values in the range $[0.05, 0.5]$ with a step of 0.01. At the last symbol of each source block the algorithm makes a random choice on the amount of redundant packets that the AL-FEC encoder will produce for this particular block. Consequently, the algorithm applies a random spread of the introduced overhead at all of the blocks the transmitted object is divided to.

Since the examined AL-FEC policy problem is a cost minimization problem, the competitive ratio c_1 of the presented randomized online Algorithm 1 can be defined as the minimum value of c for which it applies:

$$E\big[ALG_1(\sigma)\big] - c_1 \cdot OPT(\sigma) \leq \alpha \quad (4)$$

Therefore, since the definition of the AL-FEC policy problem allows to set the value of the quantity α equal to 0, the competitive ratio c_1 of the randomized online Algorithm 1 can be computed from (4) as:

$$c_1 = \max \frac{ALG_1}{OPT}$$

Subsequently, given that the expected value $E(I)$ of the random variable I is 0.275, the competitive ratio of the Algorithm 1 is:

$$c_1 = 1.275 \cdot (1 - p)$$

It is obvious that the performance of the proposed online Algorithm 1 depends on the value of the packet loss rate p an adversary will introduce. However, our objective is not to analyze the worst-case competitive ratio, but to investigate the performance of the randomized algorithm on typical packet loss scenarios.

Algorithm 1 Randomized AL-FEC Online Algorithm

procedure (pkt, sbl)
    if $pkt.uid$ mod $sbl = 0$ **then** ▷ check if the processed packet is the last of the block
        select equiprobably a value i from the set $\{0.05 : 0.01 : 0.5\}$ ▷ randomly select the introduced overhead for each source block
        transmission overhead $\leftarrow \lceil sbl * i \rceil$ ▷ assign the selected overhead to the current source block
    end if
end procedure

The proposed randomized online algorithm requires in fact just the input of the *uid* of the current packet and the selected length of each AL-FEC source block. Based on these two value, the algorithm is able to distribute the packets in source blocks and to determine the amount of protection that will be introduced in each formed block according to the random process described above.

The cost of the randomized online Algorithm 1 can be described by (3), since the number of transmitted packets is $sbl + sbl \cdot i$ per source block:

$$ALG_1 = sbl \cdot \big(1 + E(I)\big) \quad (3)$$

where $E(I)$ denotes the expected value of the random variable I.

At this point, we have to highlight that the optimal algorithm has prior knowledge of the packet loss conditions of the multicast users in contrast to the online algorithm which does not know or can not predict the outcome of the transmitted packets. This is why we investigate the performance of an a priori arbitrary choice of the introduced redundancy at a fair range of values.

Regarding the complexity of the proposed online randomized scheme, the algorithm processes a sequence of packets and formulates them in a source block od size *sbl*. For each processed packet, the algorithm indicates some lightweight $O(1)$ operations. Hence, it is straightforward that the complexity of the randomized algorithm for a source block of packets of size *sbl* is $O(sbl)$.

4.2 Weighted online AL-FEC algorithm

In this subsection we provide an adaptive online algorithm on the selection of the introduced AL-FEC transmission overhead over mobile multicast streaming environments. The proposed Algorithm 2 is based on weights assignment in each processed AL-FEC packet. The algorithm takes as input each processed packet and assigns a weight to the packet according to its unique ID. Thereafter, the algorithm determines if the processed packet will be included in the introduced redundancy, by comparing the assigned packet's weight with a selected threshold t. The value of t determines the required robustness of the AL-FEC protection. Finally, the algorithm examines if the processed packet is the last packet of the current FEC source block in order to compute the transmission overhead that will be introduced to the multicast transmission.

weights assignment process with respect to the selected threshold t.

$$\frac{log_2(pkt.uid)}{log_2(sbl)} \leq t \Rightarrow log_2(pkt.uid) \leq t \cdot log_2(sbl) \Rightarrow 2^{log_2(pkt.uid)} \leq 2^{t \cdot log_2(sbl)} \Rightarrow pkt.uid \leq \left(2^{log_2(sbl)}\right)^t \Rightarrow pkt.uid \leq sbl^t \quad (5)$$

Hence, since the number of introduced AL-FEC repair packets can be extracted by (5) according to the *uid* of the last packet passing the threshold, the cost of the weighted online Algorithm 2 in terms of the total number of transmitted packets per source block can be computed by (6):

$$ALG_2 = sbl + \lfloor sbl^t \rfloor \quad (6)$$

Consequently, according to the definition of the competitive ratio of an online algorithm as described earlier and since the online algorithm addresses a cost minimization problem its competitive ratio c_2 can be computed as:

$$c_2 = max\frac{ALG_2}{OPT}$$

Algorithm 2 Weighted AL-FEC Online Algorithm

```
procedure (pkt, sbl, t)
    pkt.w ← log2(pkt.uid)/log2(sbl)        ▷ compute the weight of the processed packet
    if pkt.w ≤ t then        ▷ determine if the processed packet will be included in the overhead
        count ← count + 1
    end if
    if pkt.uid mod sbl = 0 then  ▷ check if the processed packet is the last of the block
        transmission overhead ← count    ▷ assign the computed transmission overhead to the current source block
    end if
end procedure
```

In the above algorithm pkt, sbl, t denote each processed packet, the size of the AL-FEC source block the current packet belongs to, and the selected threshold by the multicast sender respectively. It is obvious that the *sbl* of the source block each packet is organized to can be extracted by the packet *sbn* attribute.

The presented deterministic online Algorithm 2 introduces adaptation features in AL-FEC application in the sense of the transmission overhead reduction as the length of the AL-FEC source block increases. Actually, the assigned weight of each packet decreases with the source block size increase. As a result, the algorithm introduces fewer repair AL-FEC symbols as the source block grows for a given threshold.

On the cost analysis of the proposed online Algorithm 2, the number of redundant AL-FEC packets of each source block can be easily extracted as follows according to the

Therefore, the competitive ratio c_2 of the proposed online Algorithm 2 can be computed by (6) and (2) as:

$$c_2 = (1 + sbl^{t-1})(1 - p)$$

On the complexity of the deterministic weighted online algorithm, the presented algorithm, as in the case of the randomized algorithm, processes a source block of *sbl* packets, instructing some $O(1)$ operations for each packet. Thus, the complexity of the deterministic algorithm is again $O(sbl)$ for a source block of size *sbl*.

5 Performance evaluation

In this section we provide empirical simulation results evaluating the achieved performance of the proposed online schemes compared to the optimal offline algorithm performance based on the previously described network model and utilizing the RaptorQ AL-FEC code.

5.1 Randomized algorithm evaluation over download delivery

The current subsection presents evaluation results of the proposed randomized online AL-FEC Algorithm 1 against the optimal policy algorithm performance over several perspectives. For the conducted evaluation we utilize 100 multicast users with the average packet loss rate over all mobile users varying between 1 and 10 %.

5.1.1 Recovered AL-FEC source blocks

This paragraph demonstrates simulation results on the amount of successfully decoded AL-FEC source blocks over all the multicast users. Figure 1 presents the total number of recovered source blocks over the selected packet loss rate values. For this evaluation we transmit four AL-FEC source blocks each one of size 128 source symbols.

Observing the plotted curves of Fig. 1 we can remark that the performance of the randomized online algorithm depends on the packet loss conditions that it has to confront. For low values of packet loss rate the online algorithm can operate surprisingly well, while as packet loss rate increase even more users fail to recover the transmitted source blocks. The optimal algorithm presents a much more stable performance achieving a sufficient number of successfully received source blocks across the whole range of the evaluated packet loss rate. The stable behavior of the optimal algorithm is anticipated as a direct consequence of its introduced overhead selection.

The form of the randomized online algorithm can be justified by the range of the randomly selected values of the introduced redundancy. However, we can observe that the online algorithm can cope well enough with a wide range of packet losses, while a fixed overhead policy could only operate successfully under very specific values of packet loss rates and could lead to huge waste of network resources.

To further clarify the advantages of the proposed online scheme against a fixed AL-FEC overhead policy, in Fig. 2 we provide simulation results on the average number of successfully decoded AL-FEC source blocks per multicast user. We simulate the transmission of an object partitioned to 10 source blocks each consisting of 128 source symbols, comparing the performance of the randomized online AL-FEC policy with that of a fixed overhead policy with the introduced AL-FEC overhead fixed at 5 %.

The form of the plotted curves in Fig. 2 immediately reveals the advantages offered by the random spread of the proposed online AL-FEC policy against the application of AL-FEC protection with fixed overhead. We can observe that the 5 % fixed overhead policy can provide sufficient protection only in a small range of packet loss rate, since for values greater than 6 % can achieve successful decoding of just one AL-FEC source block in average from the 10 transmitted.

This fact is not surprising since the fixed introduced overhead dictates that the AL-FEC protection can be efficient only for values of packet loss rate near to the fixed overhead. For packet losses lower than the introduced overhead, the fixed policy may indeed achieve a robust transmission but with a huge waste on network resources. At the same time, it is obvious that the fixed overhead is not capable to confront higher values of packet loss rate. On the other hand, the proposed randomized AL-FEC policy can operate fairly well under a wider range of packet loss rate achieving protection for different values of losses and providing an in average “stable” protection efficiency.

5.1.2 Total number of transmitted AL-FEC symbols

In this subsection we evaluate the total number of transmitted AL-FEC symbols, including the repair symbols, each AL-FEC policy introduces to the multicast transmission. Figure 3 presents the total number of produced AL-FEC symbols of the online and the optimal algorithm against the packet loss rate. The transmitted object is formed, as in the previous subsection, by four source blocks of 128 source symbols each one.

The plotted curves of Fig. 3 directly reflect the overhead policy mode of the optimal offline algorithm and the proposed randomized online algorithm. On the optimal offline algorithm the number of transmitted symbols, including the amount of introduced redundancy, increases in proportion to the average packet loss rate of the network. This increase directly implies from the described optimal policy since, the offline algorithm exploits its knowledge on the packet loss conditions and adapts the introduced redundancy accordingly.

On the other hand, we observe that the random overhead online algorithm introduces in average a nearly constant amount of redundant AL-FEC symbols about to 650 AL-FEC symbols varying between 130 and 180 more transmitted symbols in contrast to the amount of symbols transmitted by the offline optimal algorithm. However, the fact that the randomized online algorithm transmits a close to constant number of redundant symbols does not imply that the online algorithm operates as a fixed overhead policy. Actually, by examining several instances of the online algorithm operation, we can remark that the algorithm will introduce very different values of transmission overhead in the hope of a packet loss match. This is indeed the aim of the randomized algorithm since with no

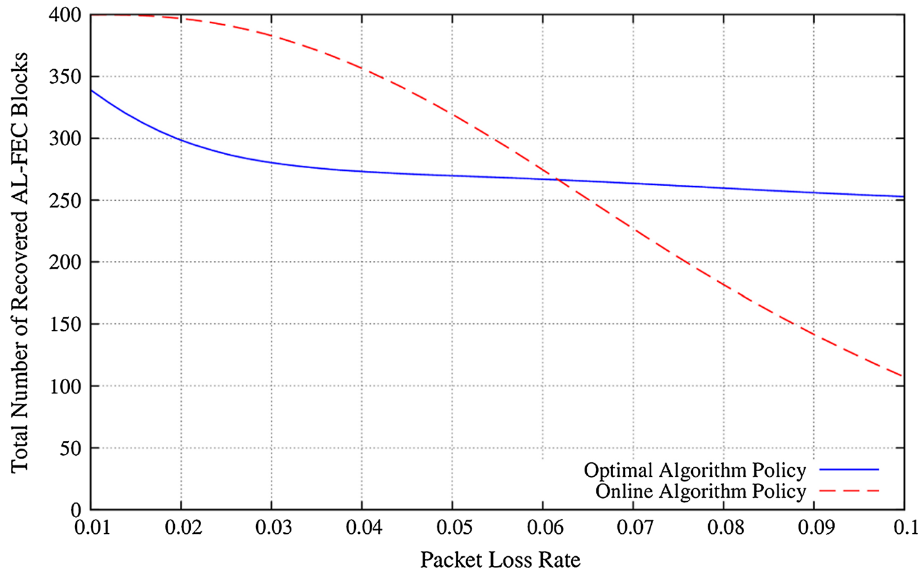

Fig. 1 Total number of recovered source blocks versus packet loss rate

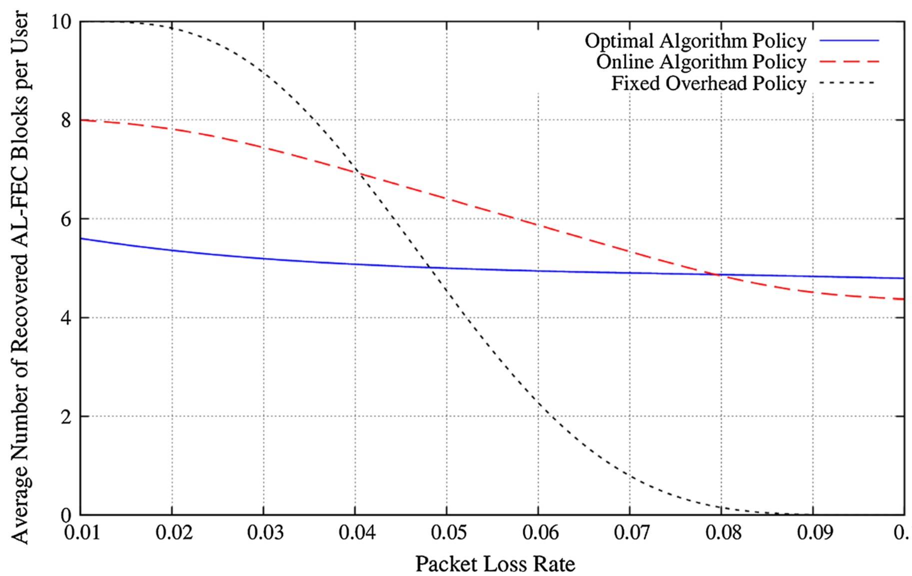

Fig. 2 Average number of recovered source blocks per user versus packet loss rate

knowledge on the network's condition and with the *sbl* fixed, attempts to achieve a sufficient performance with a random spread of the introduced overhead over different AL-FEC source blocks.

5.1.3 AL-FEC decoding failure probability

In this part of simulation results we examine the impact of the *sbl* increase on the average AL-FEC decoding failure probability of the transmitted AL-FEC source blocks. For the conduction of the simulation we utilize four transmitted source blocks of size {128, 256, 512, 1,024, 2,048, 4,096}, with the average packet loss rate fixed at 8 %. Figure 4 presents the decoding failure probability performance of the proposed online algorithm against the optimal algorithm, assuming a transmitted object of fixed size which is divided into source blocks according to the evaluated values of *sbl*.

Observing the performance results presented in Fig. 4 we can extract some very interesting remarks. It is immediately apparent that both algorithms achieve improved performance by increasing the number of AL-FEC symbols protected together in a source block. However, we can remark that the increase of the selected *sbl* benefits more the performance of the randomized online algorithm in terms of achieved average AL-FEC failure probability than the optimal offline policy. More precisely, we can observe that increasing the *sbl* from 128 to 2,048 symbols results in significant reduction on the decoding failure probability of the online algorithm from 0.14 to about 0.03, achieving a

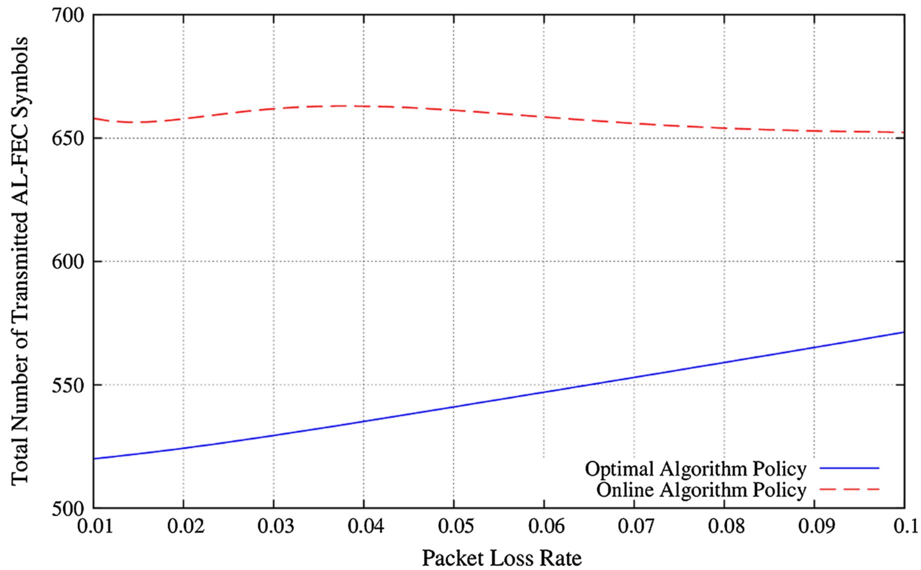

Fig. 3 Transmitted symbols versus packet loss rate

close enough performance to that of the optimal policy algorithm. The behavior of the online algorithm can be justified by the applied random spread of the introduced overhead on each AL-FEC source block, which benefits from the segmentation of the transmitted object into fewer and larger in size source blocks with the *sbl* increase.

5.2 Weighted algorithm evaluation over streaming delivery

In this subsection we present the performance evaluation of the weighted online AL-FEC Algorithm 2 providing extensive simulation results.

5.2.1 Introduced AL-FEC transmission overhead

In this paragraph, we illustrate the operation of the proposed weighted online algorithm on selecting the AL-FEC redundancy that will be introduced in the multicast transmission. More precisely, Fig. 5 presents how our online scheme adapts the introduced AL-FEC transmission overhead for different values of source block length and threshold *t*. The presented results consider source block length between 128 and 32,768 source symbols per block and the value of threshold *t* fixed at 0.8, 0.85 and 0.9.

The curves presented in Fig. 5 illustrate the AL-FEC overhead introduction policy of the presented online scheme. Analyzing the shape of the plotted curves, we can immediately remark that the proposed online algorithm follows an exponential decay on the amount of introduced AL-FEC transmission overhead as the *sbl* size increase. This fact is a direct consequence of the calculation formula for the last AL-FEC packet *uid* that will be included in the process of determining the amount of redundant AL-FEC repair symbols. Furthermore, the value of the utilized threshold *t* determines the amount of robustness a multicast sender wishes to introduce in the transmission, since the value of *t* actually determines the initial maximum value of the introduced AL-FEC transmission overhead for the minimum size of *sbl*.

Outlining in more detail the online algorithm operation, we can observe that for low values of *sbl*, i.e., for *sbl* size up to 4,096, the reduction on the introduced transmission overhead is higher than the reduction achieved for higher values of the number of AL-FEC symbols protected together within a source block. This choice was based on the fact that as the *sbl* size increase, the enhancement on the AL-FEC Raptor codes family protection efficiency between adjacent values of *sbl* is reduced, according to the works presented in [19, 20].

In the remainder of this subsection we provide empirical simulation results, illustrating how the described reduction operation of the online algorithm acts on the robustness of the AL-FEC protection and further on a streaming delivery constraints.

5.2.2 Recovered AL-FEC blocks

This part of the presented evaluation results demonstrates the protection efficiency the proposed online algorithm achieves compared to the optimal algorithm. Figure 6 demonstrates how the total number of successfully recovered AL-FEC block varies against the number of AL-FEC source symbols protected together within an AL-FEC source block. For this evaluation we examine the source block length range between 128 and 32,768 symbols, transmitting an object encoded to four source blocks to 100 multicast users with the average packet loss rate fixed to 8 % and the online algorithm threshold *t* selected to 0.7.

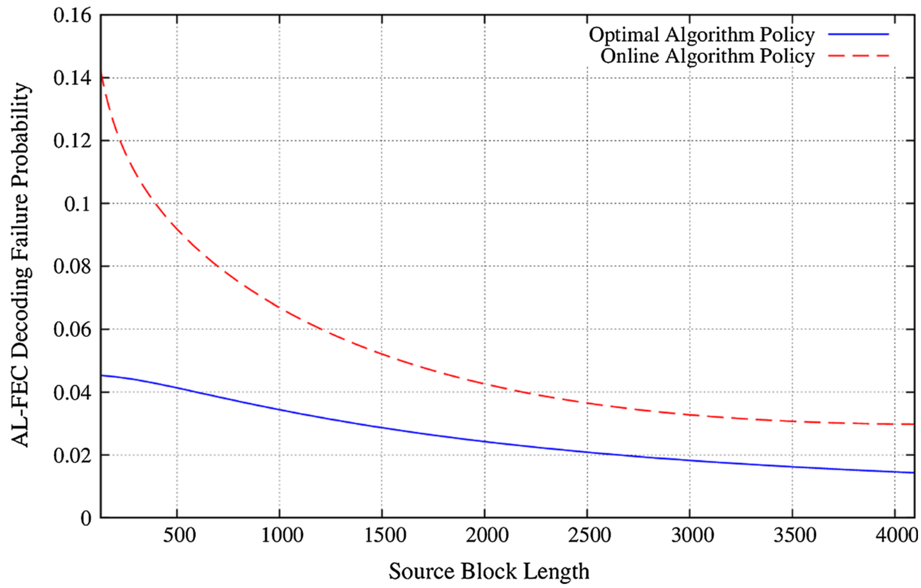

Fig. 4 Decoding failure probability versus source block length

By observing the results presented in Fig. 6 we can immediately remark that both plotted curves reflect the AL-FEC transmission overhead selection policy of both evaluated algorithms, i.e., the optimal offline algorithm and the proposed weighted online algorithm. On the optimal offline algorithm case, we can remark that as the *sbl* size increases the total number of successfully recovered AL-FEC blocks increases too. The observed increment on the number of successfully recovered blocks and consequently on the achieved protection efficiency is steeper for *sbl* values up to 4,096 symbols. This fact does not imply from the transmission overhead the optimal offline algorithm introduces in each instance of simulation. As already described in the theoretical analysis provided in Sect. 3 the optimal offline algorithm exploits its knowledge on the packet loss conditions has to confront. Based on its knowledge, the optimal algorithm introduces a fixed, in terms of percentage, transmission overhead according to the average packet loss rate and independently of the current *sbl*. Therefore, the remarked increase in the number of successfully recovered AL-FEC source blocks is due to the protection efficiency properties described in the previous subsection, i.e., as the number of AL-FEC source symbols protected together within a source block increase, RaptorQ AL-FEC achieves enhanced decoding efficiency and protection.

On the other hand, analyzing the performance of the proposed online scheme we can immediately remark that the number of successfully received AL-FEC source symbols is proportional to the *sbl* size. This fact is anticipated since as depicted in the results presented in Fig. 5 the amount of introduced AL-FEC protection is reduced with the *sbl* increase. Moreover, the form of the online algorithm curve follows the form of the introduced transmission overhead since for low values of *sbl*, i.e., up to 4,096 the number of successfully decoded AL-FEC source blocks is reduced steeper compared to higher *sbl* values where the reduction becomes ever more smooth. However, the outcome of the presented results is that even in the range of 128–4,096 *sbl* size where the reduction on the introduced transmission overhead is steep the gain on the introduced redundancy is considerably higher than the losses on transmission robustness. Indicatively we can mention that the introduced AL-FEC redundancy is reduced about almost 25 % while the number of successfully received source symbols is reduced about 12 % when the *sbl* is increased from 128 to 4,096 symbols. Moreover, comparing the minimum with the maximum value of *sbl*, the reduction on the introduced redundancy reaches the 43.5 % while the reduction on the recovered source blocks is 27.5 % achieving constantly a sufficient number of successfully received source blocks. Therefore, the online weighted algorithm can achieve significant reduction on the amount of AL-FEC redundancy providing at the same time adequate protection against packet losses.

5.2.3 *Tune-in delay reduction*

The objective of the proposed online Algorithm 2 is to introduce reliability in multicast transmission, reducing at the same time the impacts of the AL-FEC introduced redundancy on the tight constraints of a real-time service. To this direction, in this paragraph we examine the impacts of the proposed weighted online algorithm on a typical metric for the user experience of real-time services, called tune-in delay. Tune-in delay is defined as the time interval between the start of the packets reception until the start of

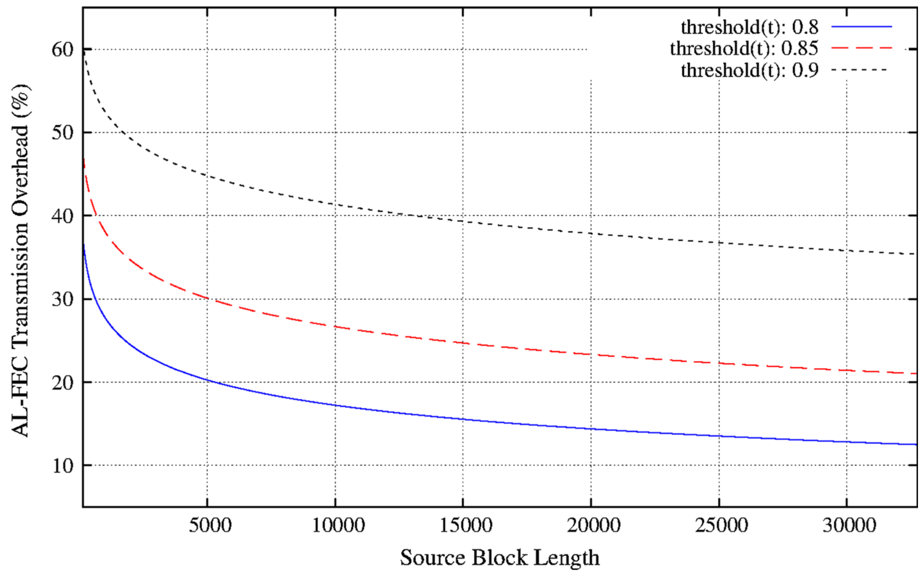

Fig. 5 Introduced AL-FEC transmission overhead versus source block length

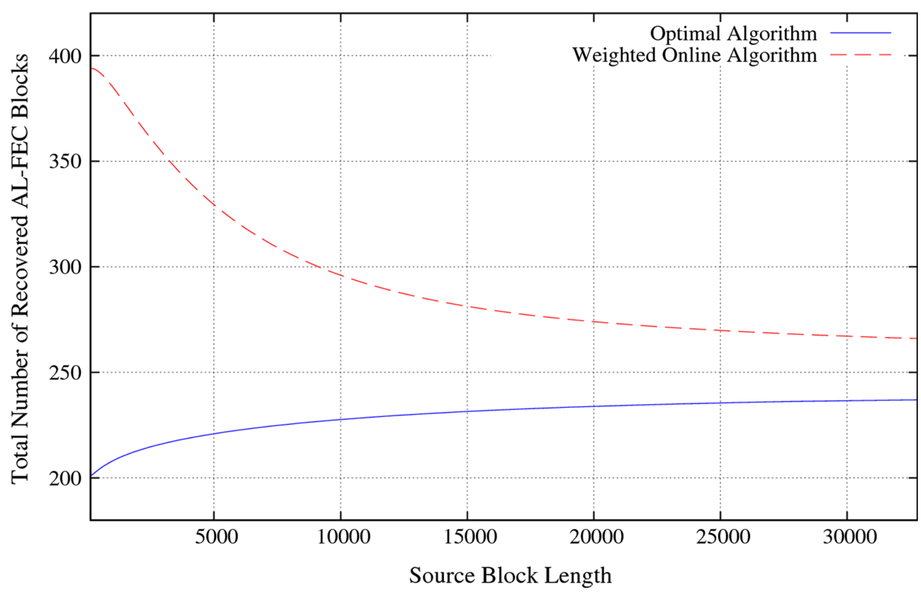

Fig. 6 Recovered AL-FEC blocks versus source block length

correct decoding the received packets of each FEC source block. Tune-in delay is experienced by a user who joins the multicast streaming session and the first received packet is anywhere but at the very start of the FEC source block. On the tune-in process a receiver first synchronizes to the FEC block, waiting for the reception and successful processing of each FEC block, before attempting to decode the media. Subsequently, the tune-in delay is a function of the FEC protection period and the decoding delay, typically defined as $\textit{tune-in delay} = \textit{protection period} + \varepsilon$ [21].

In Fig. 7 we demonstrate the reduction, in terms of percentage, on the tune-in delay the online algorithm operation achieves, comparing the measured average tune-in delay value for each evaluated source block length with the tune-in delay for the case of the smallest evaluated source block length, i.e., 128 source symbols per AL-FEC source block. Subsequently, the curve of Fig. 7 illustrates how the weighted online algorithm operation reduces the tune-in delay as the source block length increase. As in the previous part of results, we simulate 100 multicast users, with the algorithm threshold t selected to 0.7 and the transmitted object divided into four source blocks.

Observing the presented results of Fig. 7, we can immediately remark that the application of the proposed weighted online algorithm on the AL-FEC protection provides remarkable gains in the tune-in delay of a multi-cast real-time service. In more detail, we can observe that for the case of 512 symbols of *sbl* size the online algorithm achieves already a reduction in the tune-in delay of about 20 %, while for the case of the maximum evaluated *sbl*

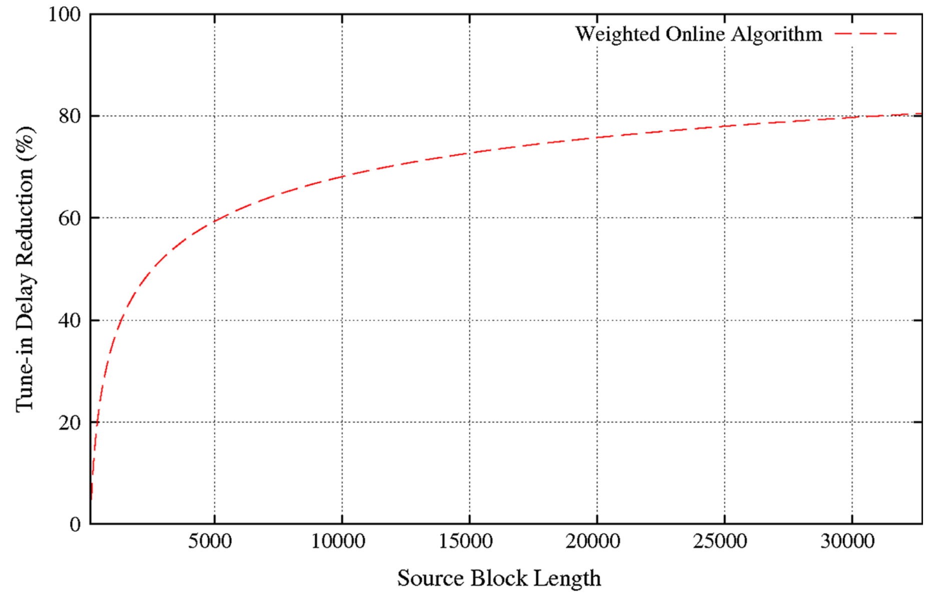

Fig. 7 Tune-in delay reduction versus source block length

size, i.e., 32,768 symbols the achieved reduction reaches the 80 %. The form of the tune-in delay reduction curve directly implies from the online algorithm operation, analyzed in the earlier Fig. 5. It is anticipated the curve of the tune-in delay reduction to be the reverse of the introduced AL-FEC transmission overhead curve, since as the *sbl* size increase the online algorithm introduces decreased AL-FEC redundancy in a source block and subsequently the achieved reduction on the tune-in delay constantly increases.

Contrasting the results presented in Fig. 7 with that in Fig. 6, we have to mention that the gains that the proposed online algorithm offers in the tune-in delay constraint of a real-time delivery is considerably higher compared to the losses on the AL-FEC protection strength as described in Fig. 6. This fact is particularly important, especially for streaming delivery where the tolerance on packet losses is higher compared to the download delivery, and the tight time constraints are essential for the overall quality of experience of a real-time service user.

6 Conclusions

In this work we have presented a novel approach on the AL-FEC application over mobile multicast services. It is the first time that the AL-FEC protection is reduced to the basis of an online problem. We have introduced the online AL-FEC policy problem which can be utilized to investigate the efficiency of several online algorithms. Furthermore, we have proposed two online algorithms to address the AL-FEC policy problem and, more precisely, we have examined two feedback-free schemes on the deployment of AL-FEC protection over mobile multicast environments utilizing RaptorQ FEC code. We have examined a randomized online AL-FEC policy scheme for download delivery aiming to effectively address the lack of knowledge on the packet loss conditions the AL-FEC protection scheme has to confront. Moreover, we have proposed a deterministic weighted online algorithm on the efficient deployment of AL-FEC protection over mobile multicast streaming services. This online scheme adapts the introduced AL-FEC transmission overhead exploiting the performance properties of the Raptor family codes according to the AL-FEC encoding parameters. To analyze the performance of the proposed online algorithms in the basis of competitive analysis, we have introduced a realistic mobile multicast network model. The presented evaluation has been based on competitive analysis, examining the performance of the proposed online AL-FEC algorithms in comparison to an offline optimal algorithm with prior knowledge of packet loss patterns as a cost minimization problem.

On the competitiveness of the randomized online algorithm, we have demonstrated that its competitive ratio depends on the various packet loss rate conditions of a multicast environment. Thereafter, we have presented simulation results of the proposed randomized online algorithm against the optimal policy algorithm examining several performance perspectives. Furthermore, we have compared the performance of the proposed randomized policy with that of a fixed overhead AL-FEC application. From the presented simulation results, we were able to verify the efficiency of the proposed online scheme and its superiority against a fixed AL-FEC overhead policy. We have demonstrated that the arbitrary random selection of the introduced AL-FEC transmission overhead can operate well enough in a reasonable range of packet loss rates, offering the possibility of the overhead spread and reducing the introduced redundancy exploiting different AL-FEC encoding parameters.

On the proposed deterministic weighted online algorithm, we have demonstrated that its competitive ratio depends on the AL-FEC encoding parameters and, more specifically, on the number of AL-FEC source symbols protected together within an AL-FEC source block. Thereafter, we have presented an operation analysis of the online scheme and furthermore we have provided simulation results on the performance of the proposed online algorithm examining the achieved protection efficiency and the impacts on the time constraints of a real-time service. From the extracted simulation results, we were able to verify that the online scheme can provide robustness on a multicast real-time delivery while at the same time can reduce the introduced AL-FEC redundancy. We have demonstrated that the reduction on the transmission overhead as the size of *sbl* increase is beneficial for a real-time delivery multicast environment since the proposed online scheme exploits the extraordinary performance properties of the powerful RaptorQ AL-FEC code providing a trade-off between transmission robustness and user experience.

7 Future work

Some possible future steps that can follow this work are the extension of the proposed weighted online algorithm with an evolved weight assignment mechanism which will utilize several AL-FEC encoding parameters as well as network parameters. Another direction could be the design of a more sophisticated online algorithm which, utilizing a feedback report mechanism on the network conditions, could adapt the introduced AL-FEC transmission redundancy. Furthermore, it is our belief that an online cross-layer scheme adapting the AL-FEC encoding parameters on the application layer considering the amount of protection on lower layers could be beneficial for the protection efficiency of a multicast transmission. Finally, we could investigate the feasibility of utilizing online algorithms on the application of AL-FEC protection over unicast mobile environments.

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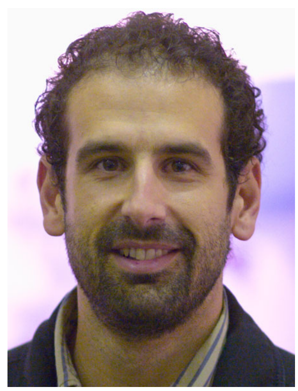

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